

Sandbjerg 2012

Quantum Optomechanics and Gravity

connecting loose ends ...

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Faculty of Physics
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Old Syme 8. VIII. 35.

Lieber Schrödinger!

Du bist faktisch der einzige Mensch mit dem ich
noch wirklich gerne auseinandersetze. Fast alle die
Kerle scheen nämlich nicht von den Thatbeständen
aus die Theorie sondern nur von der Theorie aus die
Thatbestände; sie können aus ~~ihren~~ ^{ihrem} eigenen dem
eigentlich angenommenen Begriffssatz nicht heraus
sondern nur passierlich daraus herumzappeln. Du aber
schaußt es nach Wunsche von aussen und von innen
an. Dabei sind wir in der Erfassung des zu erwartenden
Weges schärfste Gegensätze.



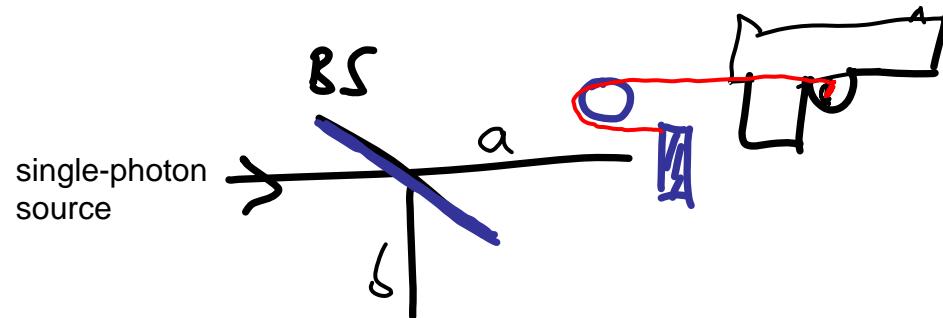
Einstein's gun powder & Schrödinger's cat

Das System sei eine Substanz in einem chemisch labilen Gleichgewicht, etwa ein Haufen Schießpulver, der sich durch innere Kräfte entzünden kann, wobei die mittlere Lebensdauer von der Größenordnung eines Jahres sei. Dies lässt sich im Prinzip ganz leicht quantenmechanisch darstellen. ~~Die~~
^{charakterisiert} Auf ~~die~~ ^{die} ~~Funktion~~
^{entkroatischen Zustand} definierten ~~Form~~
^{Nat} ~~gezeichnet~~ Gleichung sorgt aber dafür, dass dies nach Verlauf eines Jahres gar nicht mehr der Fall ist. Die ψ -Funktion beschreibt dann vielmehr eine Art Gemisch von noch nicht und vor bereits explodiertem System. Durch keine Interpretations-Kunst kann diese ψ -Funktion zu einer adäquaten Beschreibung eines wirklichen Sachverhaltes gemacht werden; in Wahrheit gibt es eben zwischen explodiert und nicht explodiert kein Zwischenring. Diese Gleichung kann also sicherlich nicht die Beschreibung des tatsächlichen Vorganges geben, wie es Dir doch vorschreibt. (Wohl aber kann es in statistischen Sinne die Aenderungen einer System-Gesundheit richtig wiedergeben). Ich will mit diesem Beispiel andeuten, dass Deine Interpretationsversuch an dem versagt, was wir als grob makroskopische Erfahrung nicht wissen...)

Albert Einstein to Erwin Schrödinger, 8.8.1935

Schrödinger's Cat: The Measurement Problem

E. Schrödinger, Naturwissenschaften 23, 52 ff. (1935)



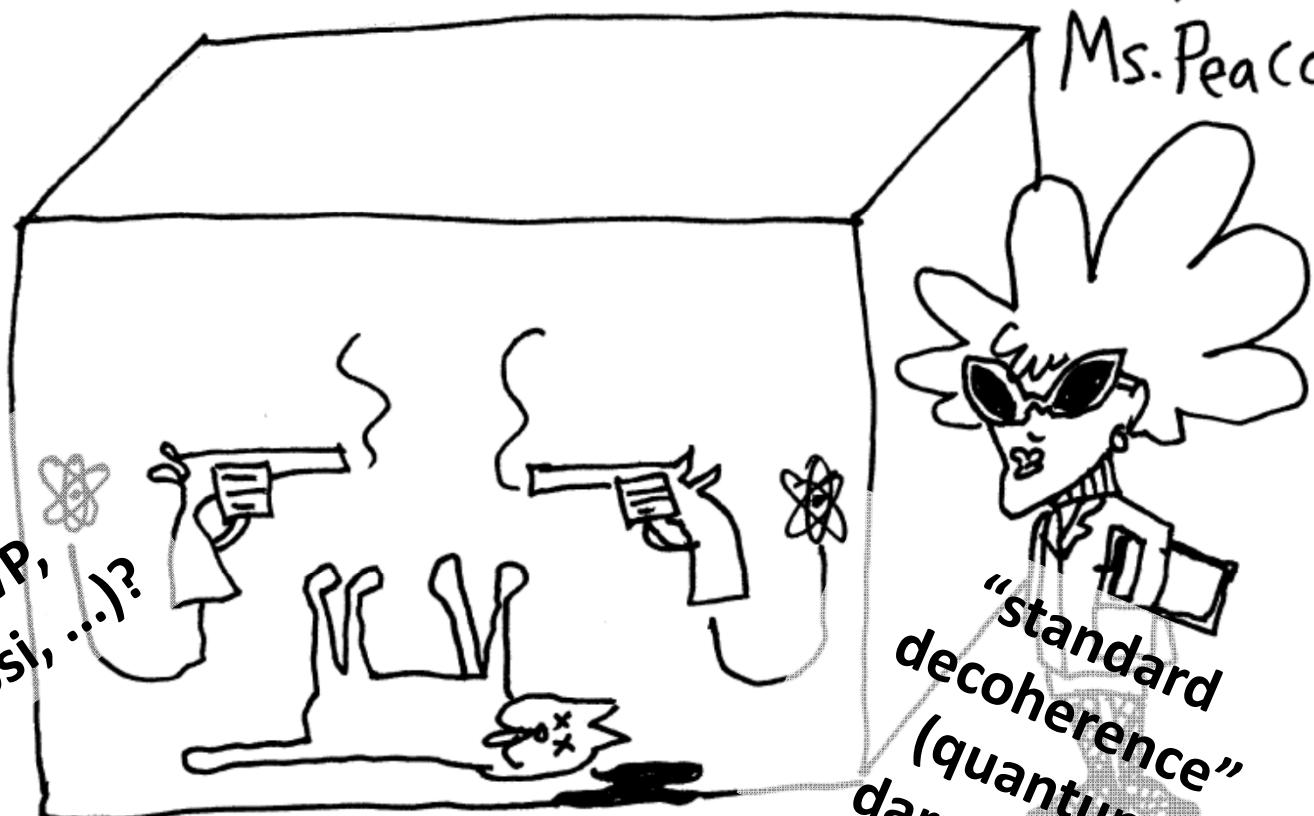
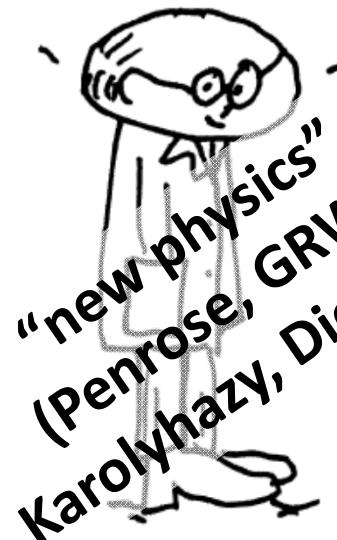
$$|0\rangle_a + |1\rangle_a \rightarrow |0\rangle_a / \begin{array}{c} \text{cat} \\ \boxed{\text{cat}} \end{array} + |1\rangle_a / \begin{array}{c} \text{cat} \\ \boxed{\text{XX}} \end{array}$$

Schrödinger's Cat = Entanglement involving **macroscopically distinct states**
→ should be possible for **arbitrarily large systems**

WHO KILLED SCHRÖDINGER'S CAT?

WAS it...

Colonel
Mustard?



"standard
decoherence
(quantum
darwinism)?

18

(c) Oppenheim

Macroscopic Quantum Experiments (some examples)

Nature 406, 43 (2000)

Quantum superposition of distinct macroscopic states

Jonathan R. Friedman, Vijay Patel, W. Chen, S. K. Tolpygo & J. E. Lukens

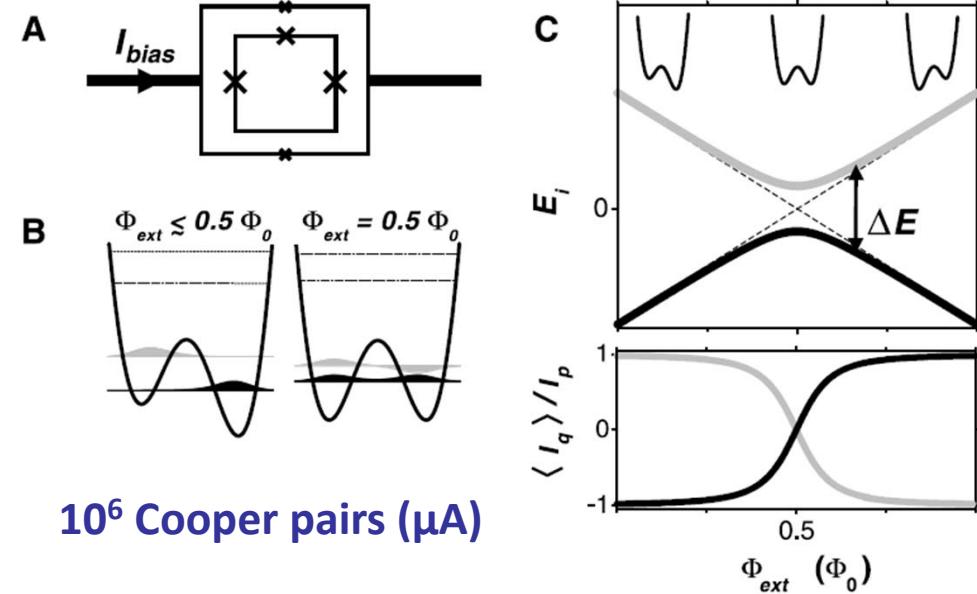
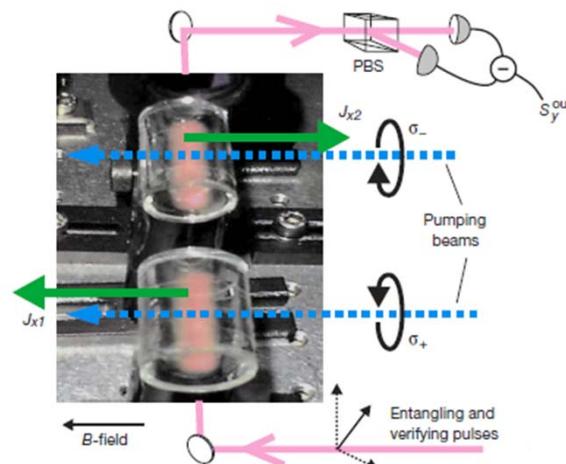
Department of Physics and Astronomy, The State University of New York, Stony Brook, New York 11794-3800, USA

Science 290, 773 (2000)

Quantum Superposition of Macroscopic Persistent-Current States

Casper H. van der Wal,^{1,*} A. C. J. ter Haar,¹ F. K. Wilhelm,¹
R. N. Schouten,¹ C. J. P. M. Harmans,¹ T. P. Orlando,²
Seth Lloyd,³ J. E. Mooij^{1,2}

2-mode spin squeezing of 10^{12} Rb atoms



10^6 Cooper pairs (μA)

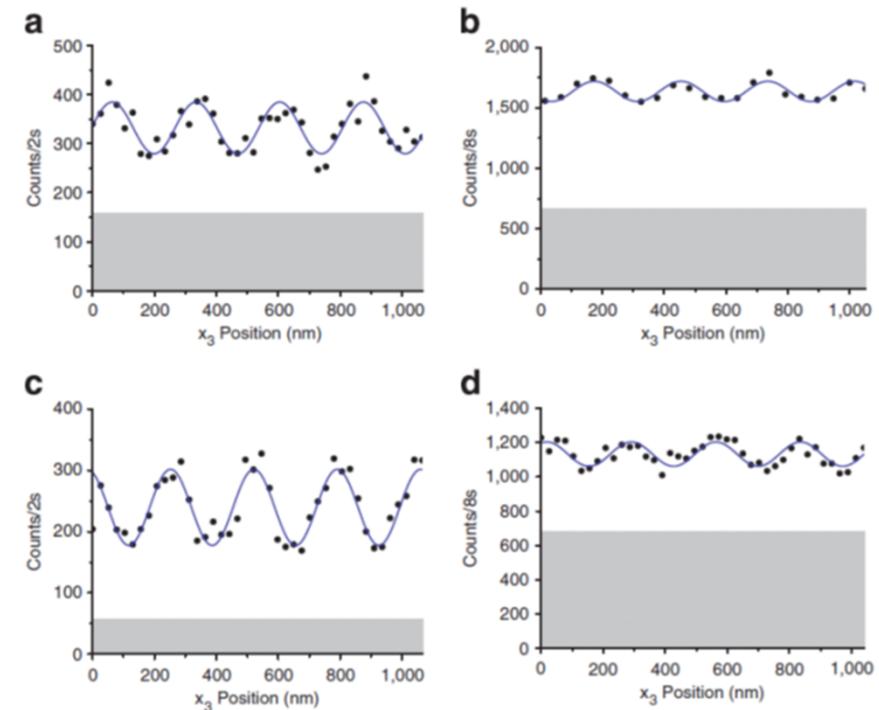
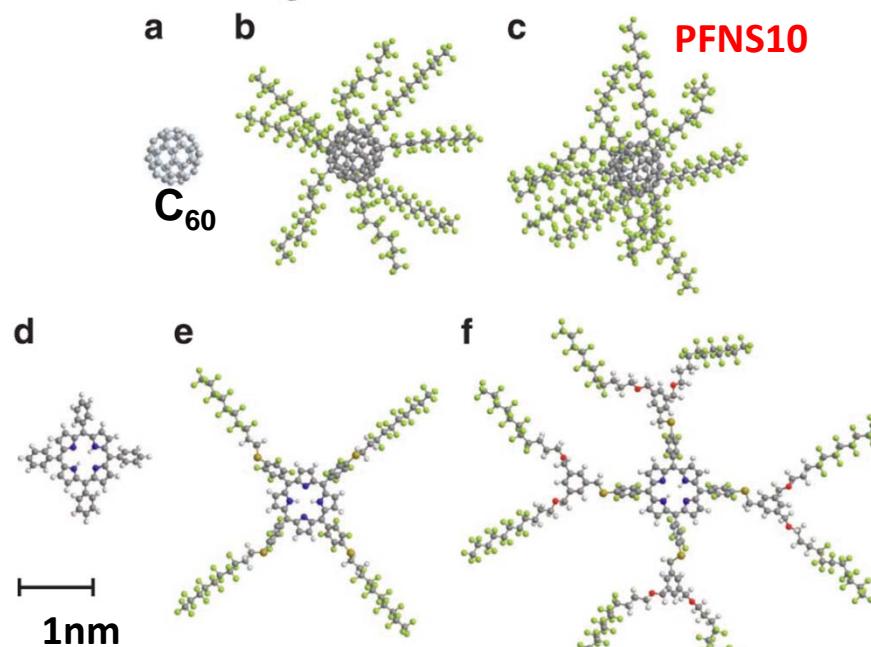
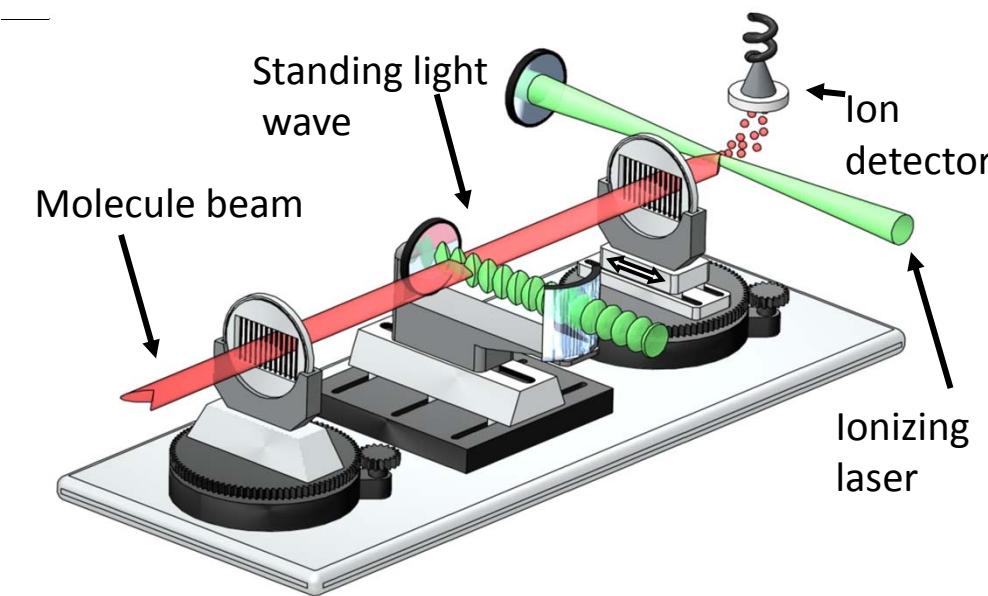
Nature 413, 400 (2001)

Experimental long-lived entanglement of two macroscopic objects

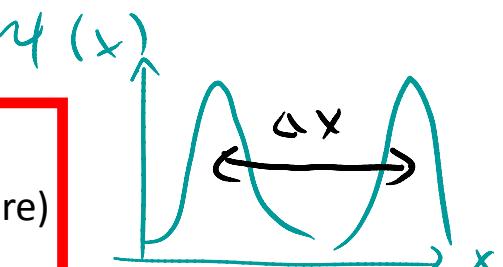
Brian Julsgaard, Alexander Kozhekin & Eugene S. Polzik

Institute of Physics and Astronomy, University of Aarhus, 8000 Aarhus, Denmark

Talbot-Lau Interferometry with Macromolecules (Arndt group)



PFNS10: C₆₀[C₁₂F₂₅]₁₀
(perfluoroalkylated nanosphere)
430 atoms
 $m \sim 10^{-23} \text{ kg} = 6910 \text{ AMU}$
 $\Delta x \sim 100 \text{ nm}$ (~ 50 times its diameter)

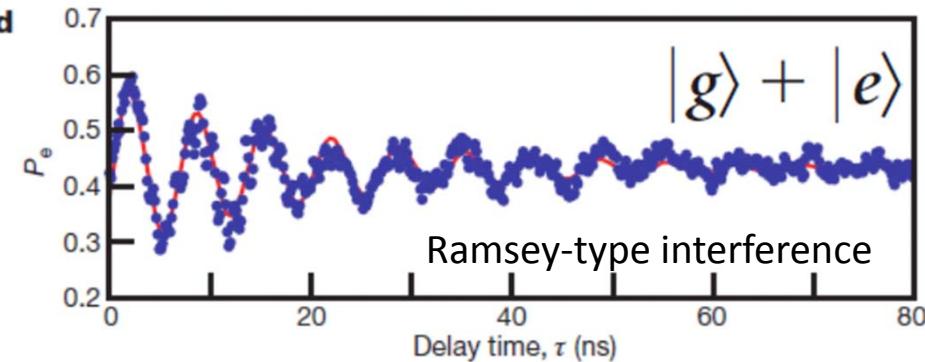
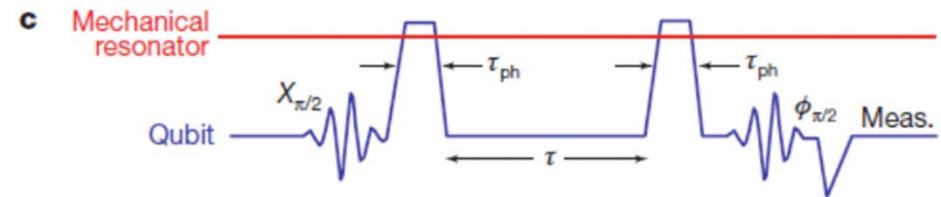
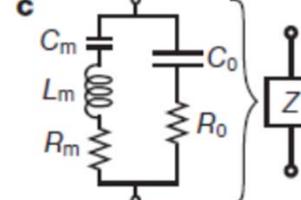
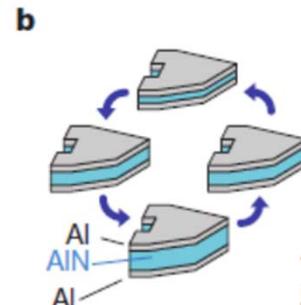
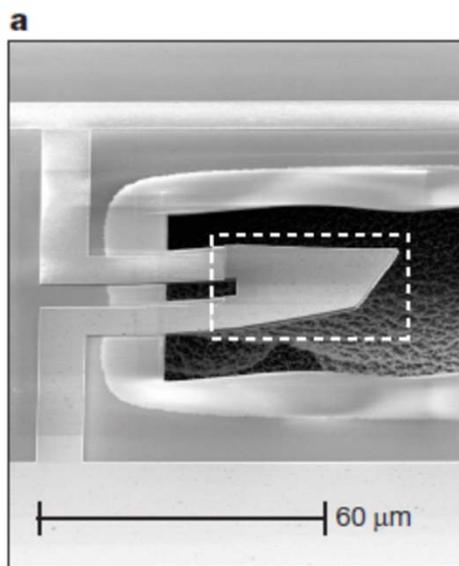


6 GHz thickness oscillation
 $\rightarrow n \sim 0.07 @ 20 \text{ mK}$

ARTICLES

Quantum ground state and single-phonon control of a mechanical resonator

A. D. O'Connell¹, M. Hofheinz¹, M. Ansmann¹, Radoslaw C. Bialczak¹, M. Lenander¹, Erik Lucero¹, M. Neeley¹, D. Sank¹, H. Wang¹, M. Weides¹, J. Wenner¹, John M. Martinis¹ & A. N. Cleland¹



Neutron, 1 „atom“

$m \sim 10^{-27} \text{ kg} = 1 \text{ AMU}$

$\Delta x \sim 1 \text{ cm}$

($\sim 10^{13} \times$ its diameter)

PFNS10: $C_{60}[C_{12}F_{25}]_{10}$, 430 atoms

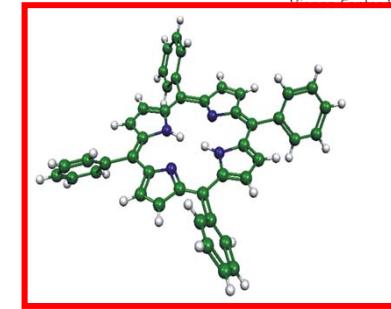
$m \sim 10^{-23} \text{ kg} = 6910 \text{ AMU}$

$\Delta x \sim 100 \text{ nm}$ ($\sim 50 \times$ its diameter)

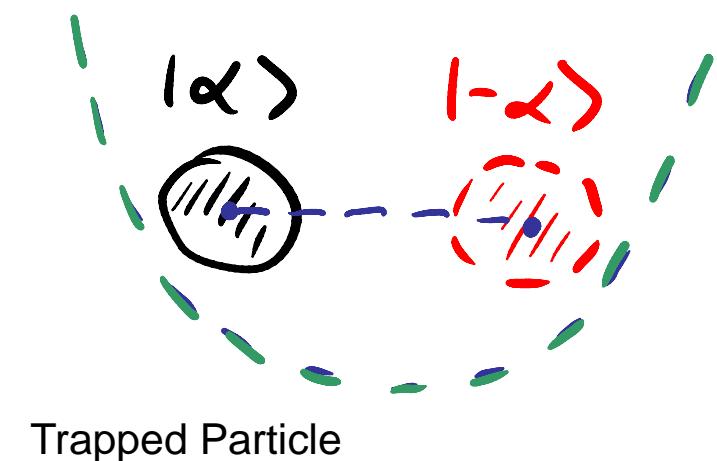
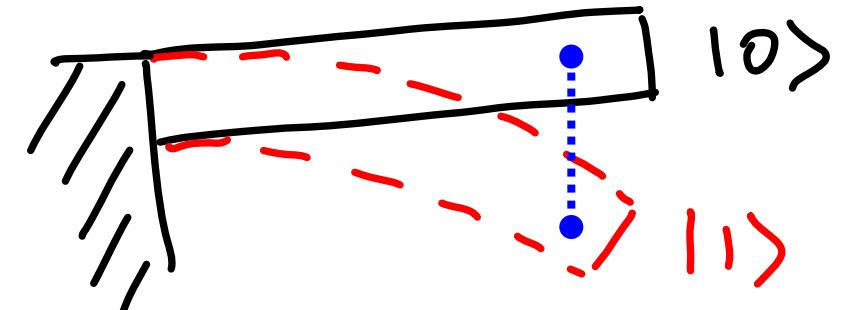
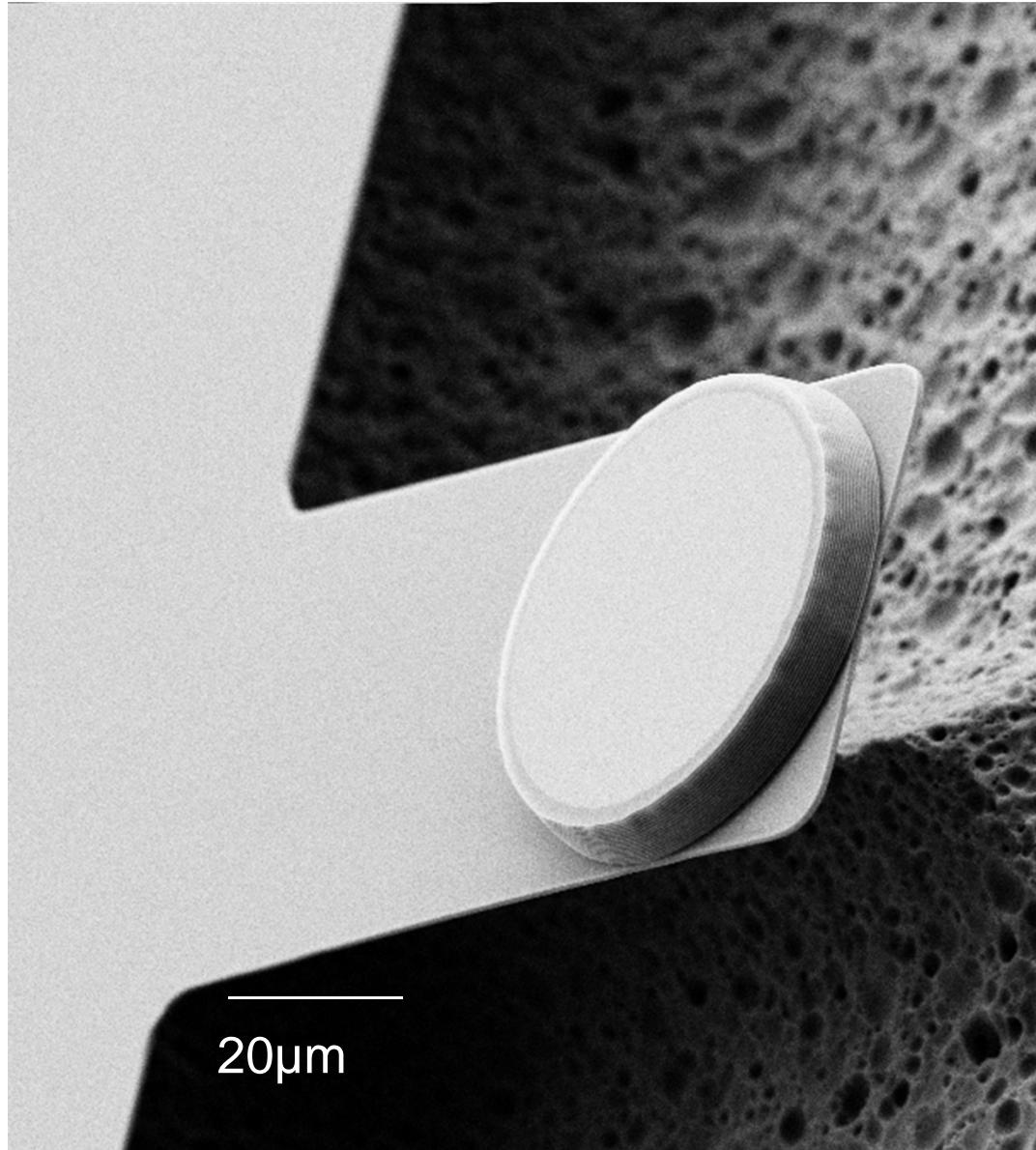
Micromechanics, 2×10^{13} atoms

$m \sim 10^{-12} \text{ kg} = 7 \times 10^{14} \text{ AMU}$

$\Delta x \sim 10^{-16} \text{ m}$ ($\sim 10^{-10} \times$ its diameter)



A mechanical cat? Schrödinger's mirrors





Levitating frog...

M. V. Berry and A. K. Geim, Of flying frogs and levitrons,
Eur.J.Phys 18, 307 (1997)
IG Nobel Prize 2000

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] + \mathcal{L}[\rho]$$

Master equation approach

$$\langle x | \mathcal{L}_g[\rho] | x' \rangle = \begin{cases} -[\Delta x]^2 \Lambda_g \langle x | \rho | x' \rangle, & \Delta x < \frac{\hbar}{m\bar{v}} \\ -\Gamma'_g \langle x | \rho | x' \rangle, & \Delta x > \frac{\hbar}{m\bar{v}}. \end{cases}$$

where

$$\Lambda_g = \frac{3m\bar{v}P\pi R^2}{\hbar^2}$$

$$\Gamma'_g = \frac{\pi R^2 P}{m\bar{v}}$$

$$\langle x | \mathcal{L}_g[\rho] | x' \rangle = \begin{cases} -\Lambda_P \Delta x^2 \langle x | \rho | x' \rangle, & \Delta x \ll R \\ \Lambda_P \langle x | \rho | x' \rangle, & \Delta x > R. \end{cases}$$

$$\Lambda_P = \Lambda_D = \frac{20\rho^2 R^3}{\hbar}, \quad \Delta x \ll R$$

$$\Lambda'_P = \frac{20\rho^2 R^5}{\hbar}, \quad \Delta x \geq R.$$

Gas scattering

See also

O. Romero-Isart et al.,
 PRL 107, 020405
 (2011)
 O. Romero-Isart, PRA
 84, 052121 (2011)

Penrose model

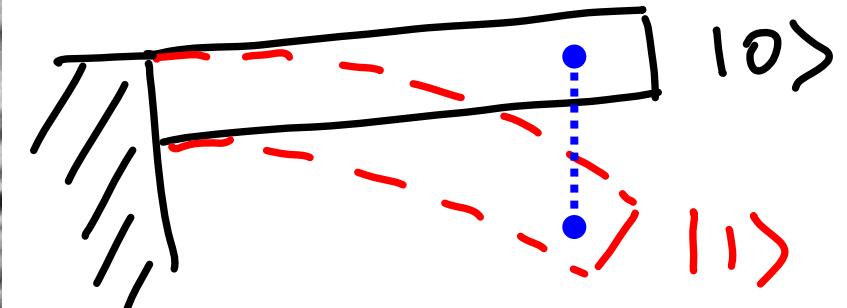
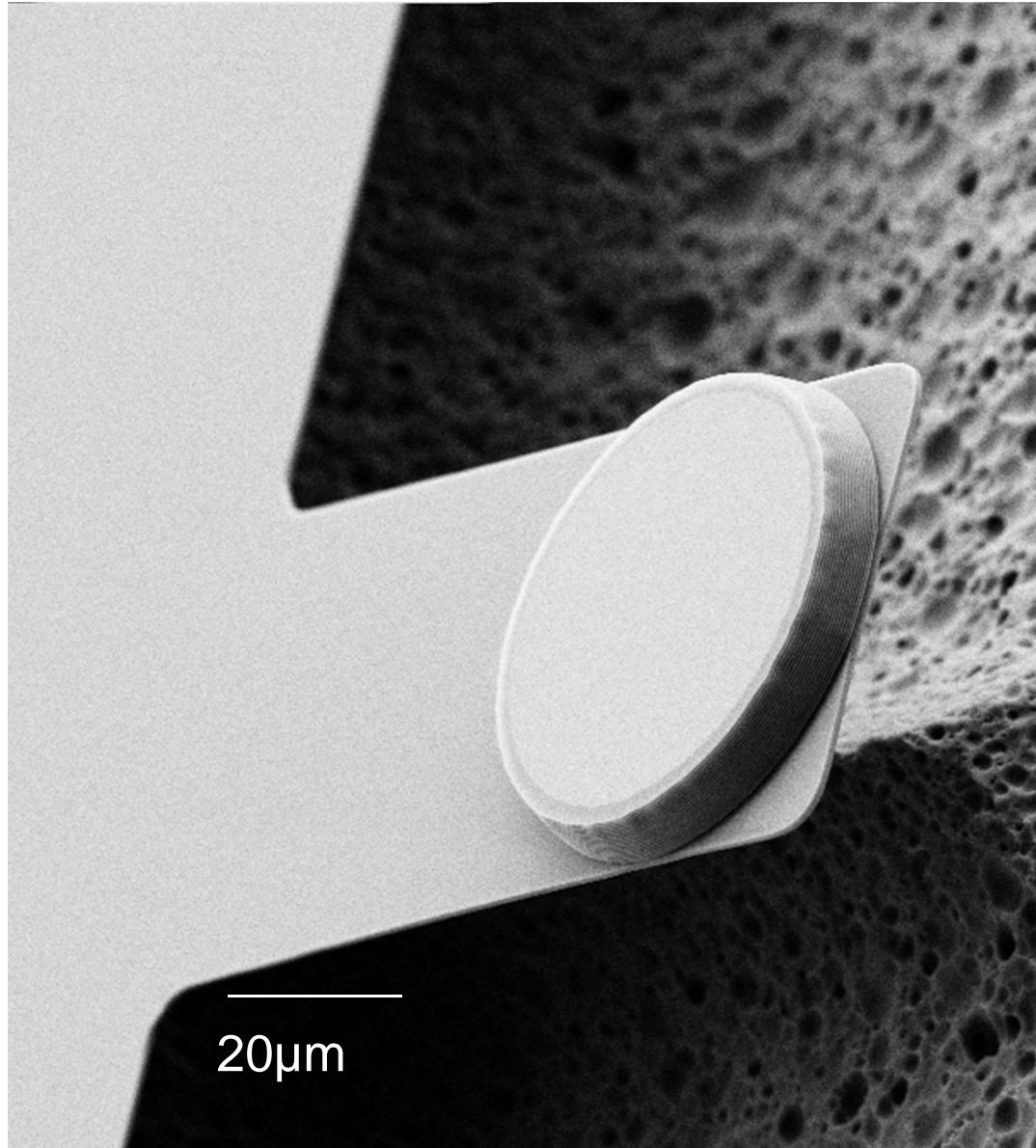
GRWP

$$\Lambda_{\text{CSL}} = m^2 \lambda_0 \alpha f(\sqrt{\alpha}R) / (2m_0^2)$$

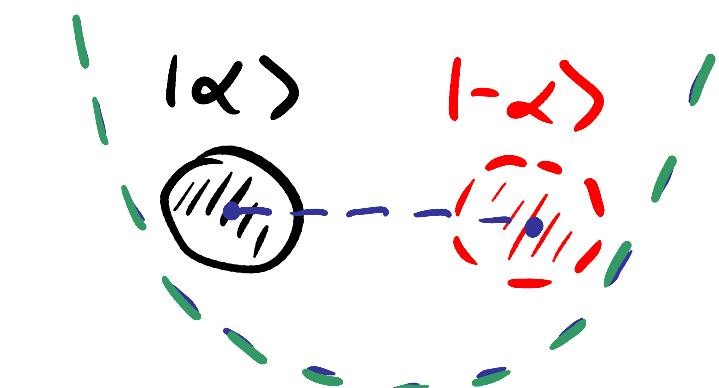
$$\alpha^{-1/2} \approx 10^{-7} \text{ m}$$

$$\lambda_0 \approx 2.2 \times 10^{-17} \text{ s}^{-1}$$

A mechanical cat? Schrödinger's mirrors



Cantilever



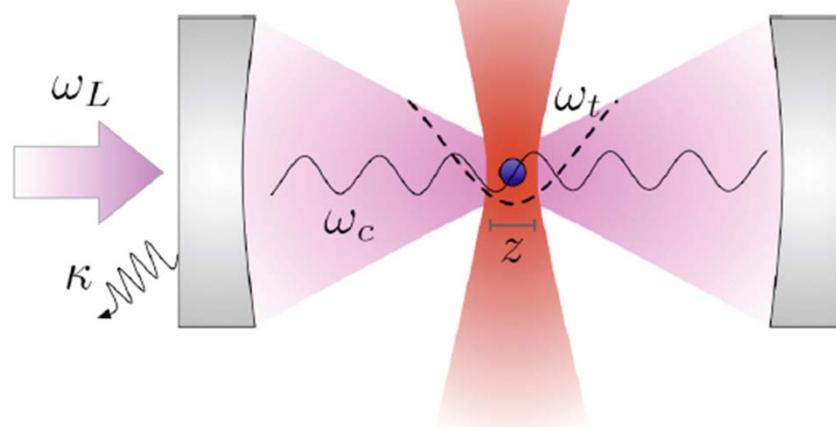
Trapped Particle

Optically levitated nanospheres

Magnetically levitated spheres

(Romero-Isart et al., 1112.5609
Cirio et al., 1112.5208)

Chang et al., quant-ph 0909.1548 (2009), PNAS 2010
Romero-Isart et al., quant-ph 0909.1469 (2009), NJP 2010
P. F. Barker et al., PRA 2010



→ Harmonic oscillator in optical potential
(negligible support loss, high Q)

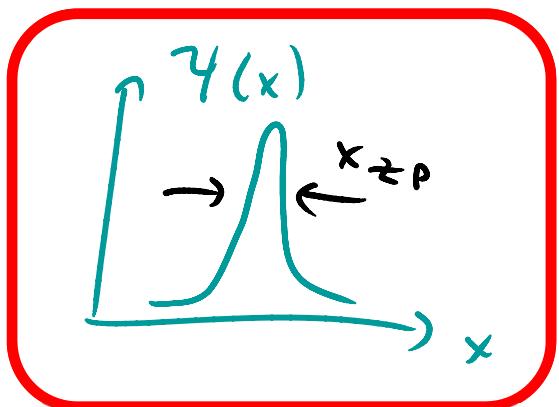
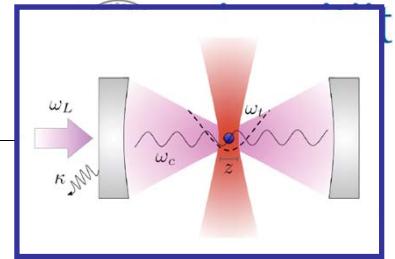
→ Quantum control via cavity optomechanics
(laser cooling, state transfer, etc.)

Generation of quantum superposition states

- single-photon quantum state transfer
- quantum state teleportation
- ...
- *free fall . . .*

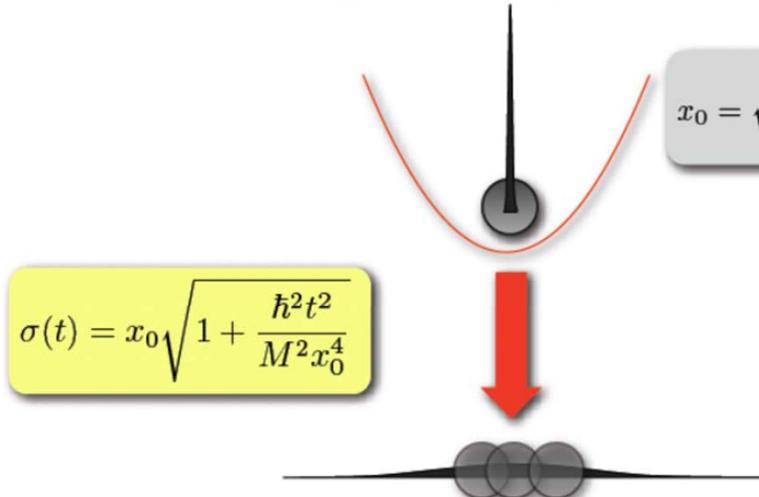
- Akram, Kiesel, Aspelmeyer, Milburn, NJP 12, 083030 (2010)
- Khalili, Danilishin, Miao, Müller-Ebhardt, Yang, Chen, quant-ph 1001.3738 (2010)
- Romero-Isart, Pflanzer, Juan, Quidant, Kiesel, Aspelmeyer, Cirac, Phys. Rev. A 83, 013803 (2011)

Superposition of macroscopic distinct states via free fall?

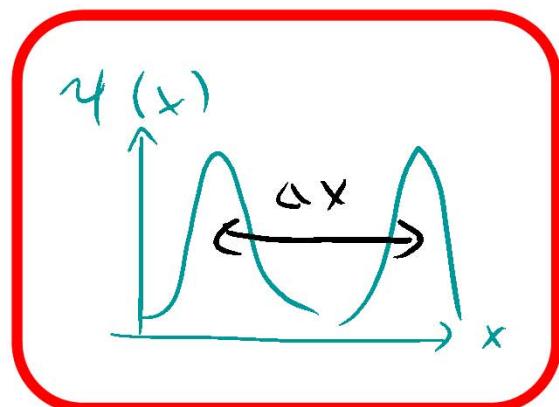


Proposal

- Ground state cooling + time-of-flight

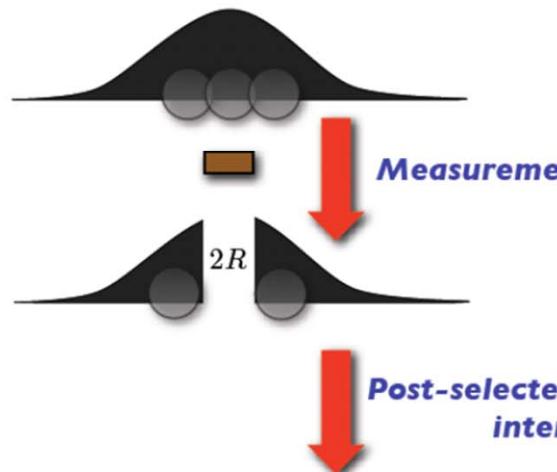


$$\begin{aligned} R &= 50 \text{nm} \\ t &= 5 \text{ms} \\ \sigma(t) &> 2R \end{aligned}$$

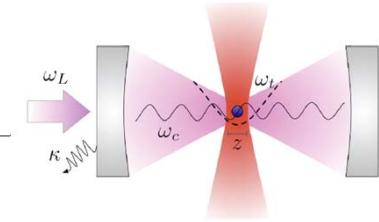


No standard decoherence

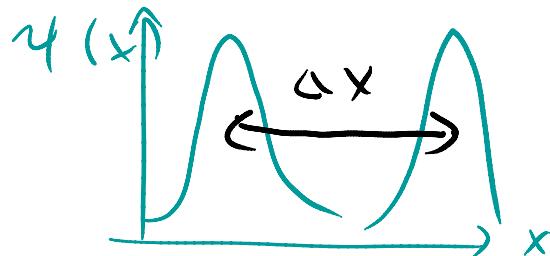
$$t_{\text{flight}} \ll 1/\Gamma_{\text{gas}}$$



One possible application: test of alternative decoherence models



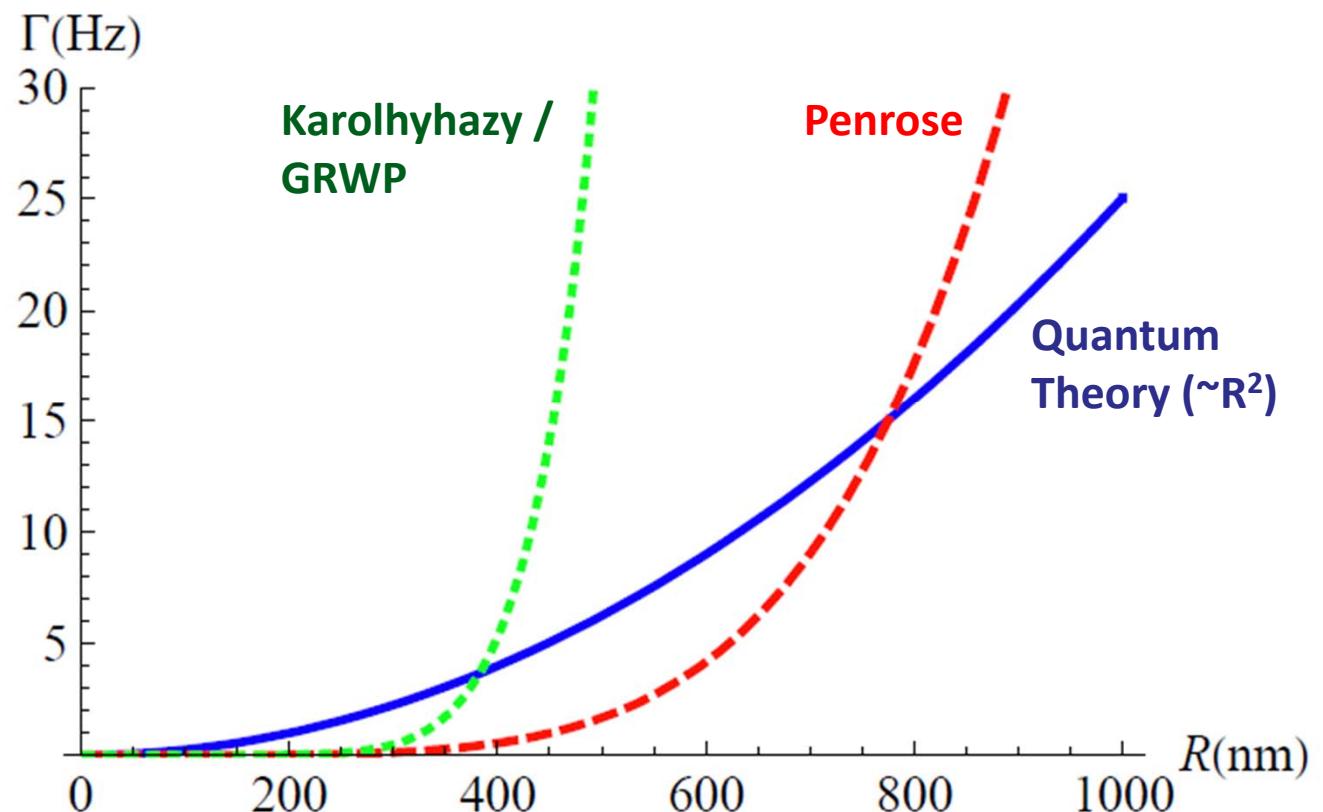
O. Romero-Isart et al., PRL 107, 020405 (2011)



$$\Delta x \sim R$$

Background gas
 $p \sim 10^{-13}$ mbar

(here: no
blackbody
radiation!)



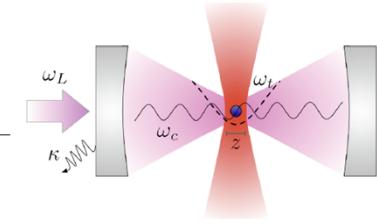
Karolyhazy (1960s), e.g. Nuovo Cimento 42, 390 (1966)

Diosi (1980s), e.g. J. Phys. A: Math. Gen. 21, 2885 (1988)

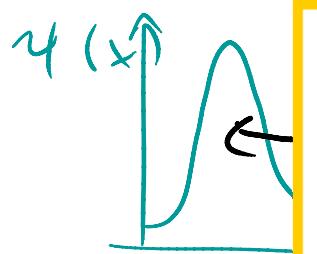
Penrose (1980s), e.g. Gen. Rel. Grav. 34, 1141 (2002)

In collaboration with O. Romero-Isart, A. Pflanzer, I. Cirac
see also Romero-Isart, Phys. Rev. A 84, 052121 (2011)

One possible application: test of alternative decoherence models



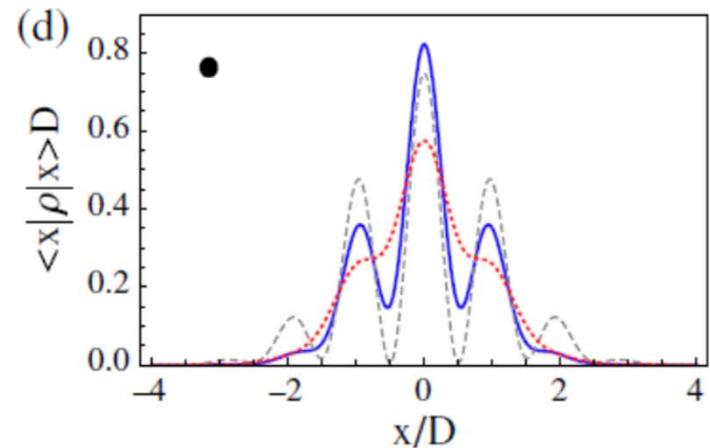
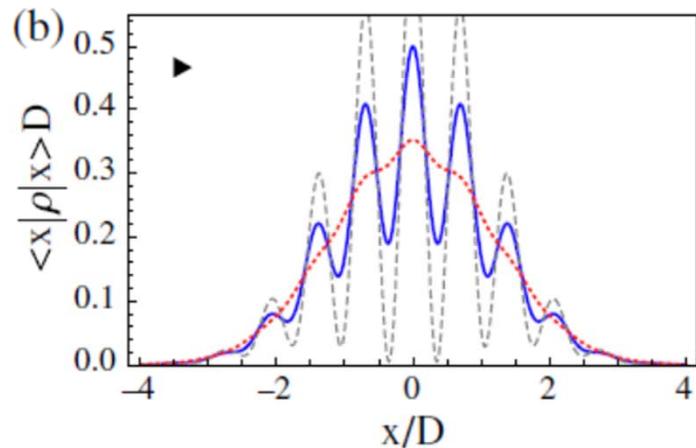
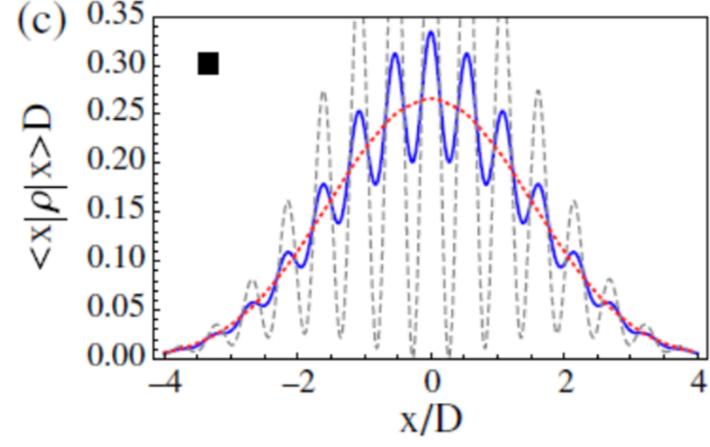
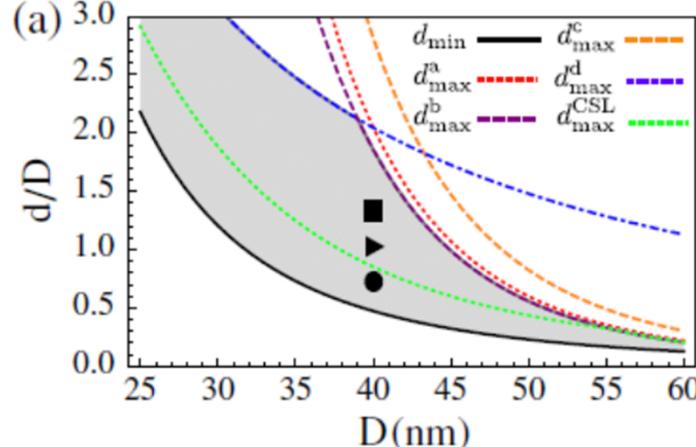
O. Romero-Isart et al., PRL 107, 020405 (2011)



$\Delta x \sim R$

Background
 $p \sim 10^{-13}$

(here: n blackbody radiation)



Karolyhazy (1980s), e.g. Nuovo Cimento 42, 590 (1980)

Diosi (1980s), e.g. J. Phys. A: Math. Gen. 21, 2885 (1988)

Penrose (1980s), e.g. Gen. Rel. Grav. 34, 1141 (2002)

$P \sim 10^{-13} \text{ mbar}, T \sim 4\text{K}$

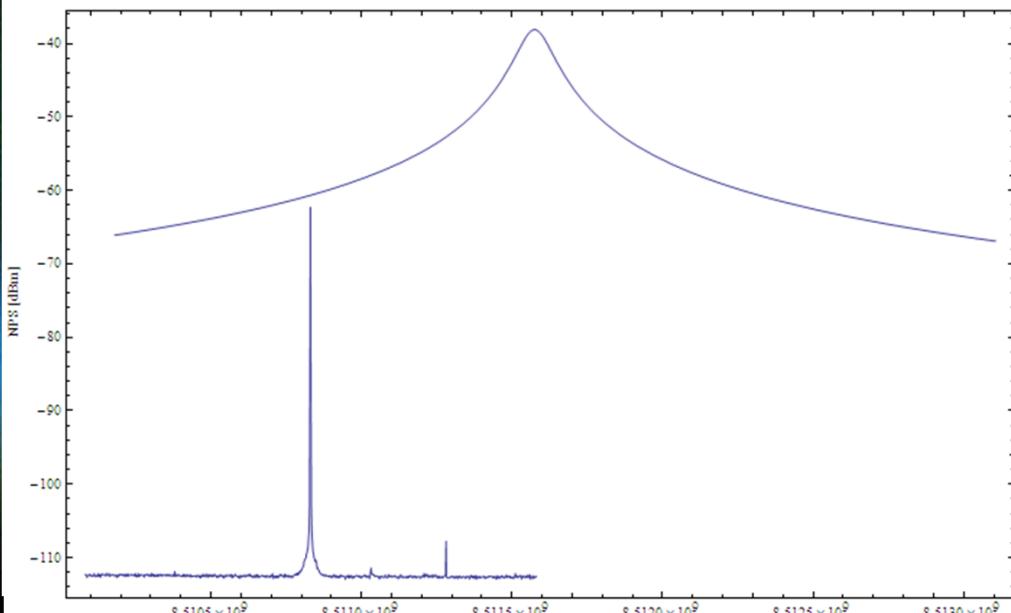
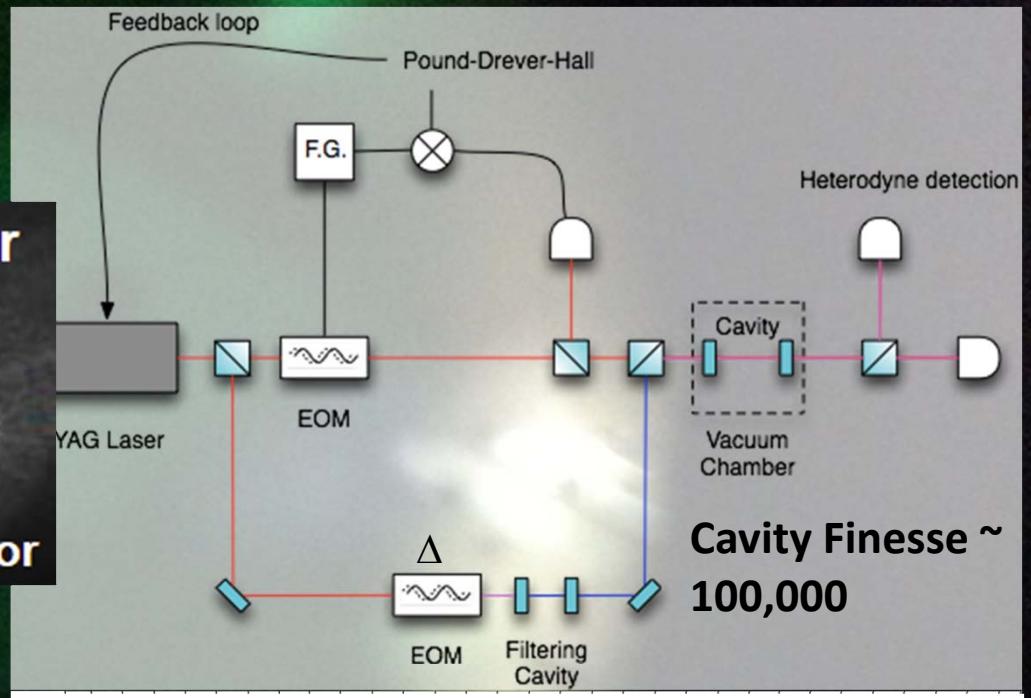
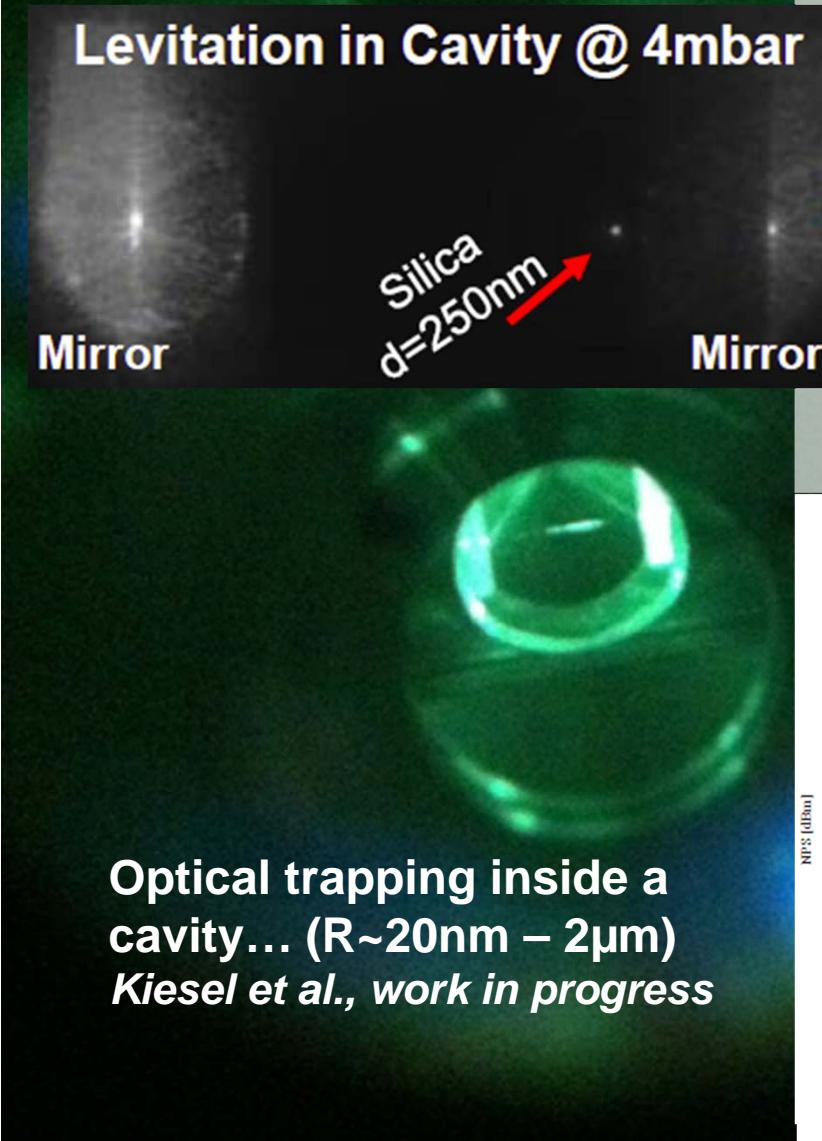
In collaboration with O. Romero-Isart, A. Pflanzer, I. Cirac
see also Romero-Isart, Phys. Rev. A 84, 052121 (2011)

Optically trapped nanospheres as mechanical resonators

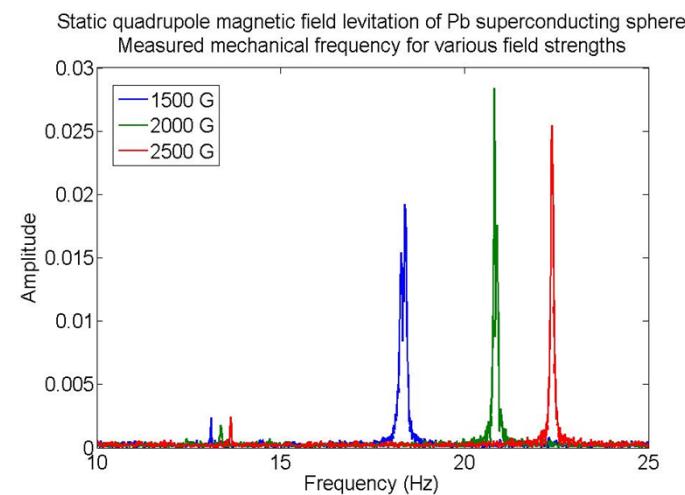
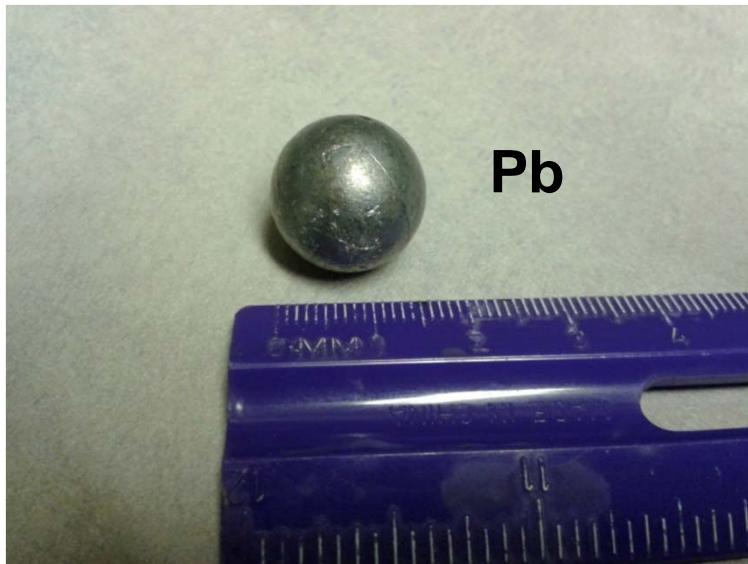
Ashkin since 1967

Raizen group, Science 2010

Novotny 2012



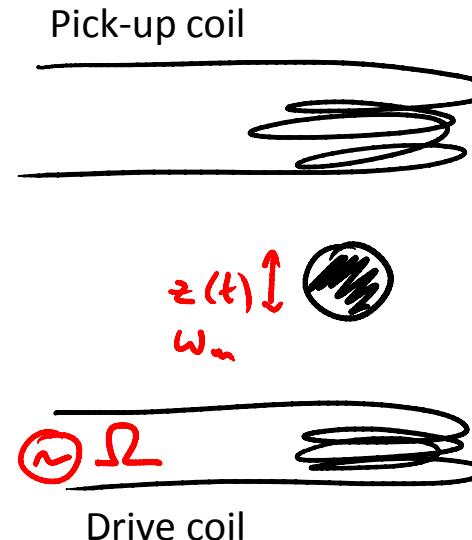
Magnetically trapped macrospheres as mechanical resonators



Magnetic levitation in anti-Helmholtz coil configuration

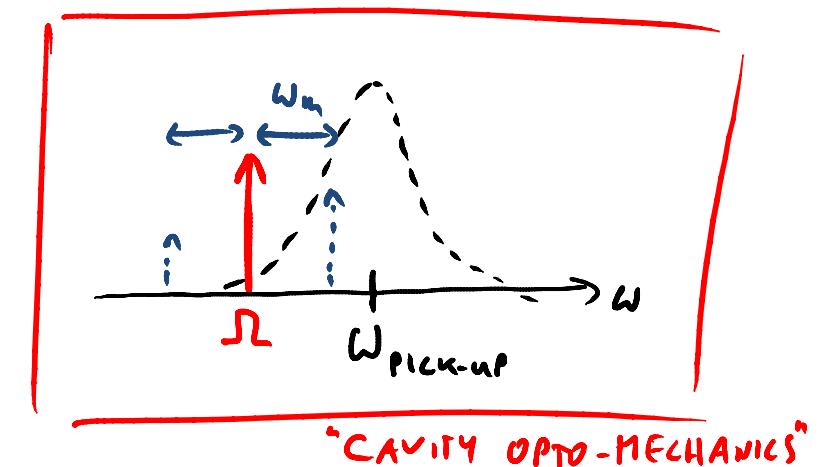
Trap frequencies ~ 20 Hz

$T = 20$ mK, $p = 1\text{e}-6$ mbar

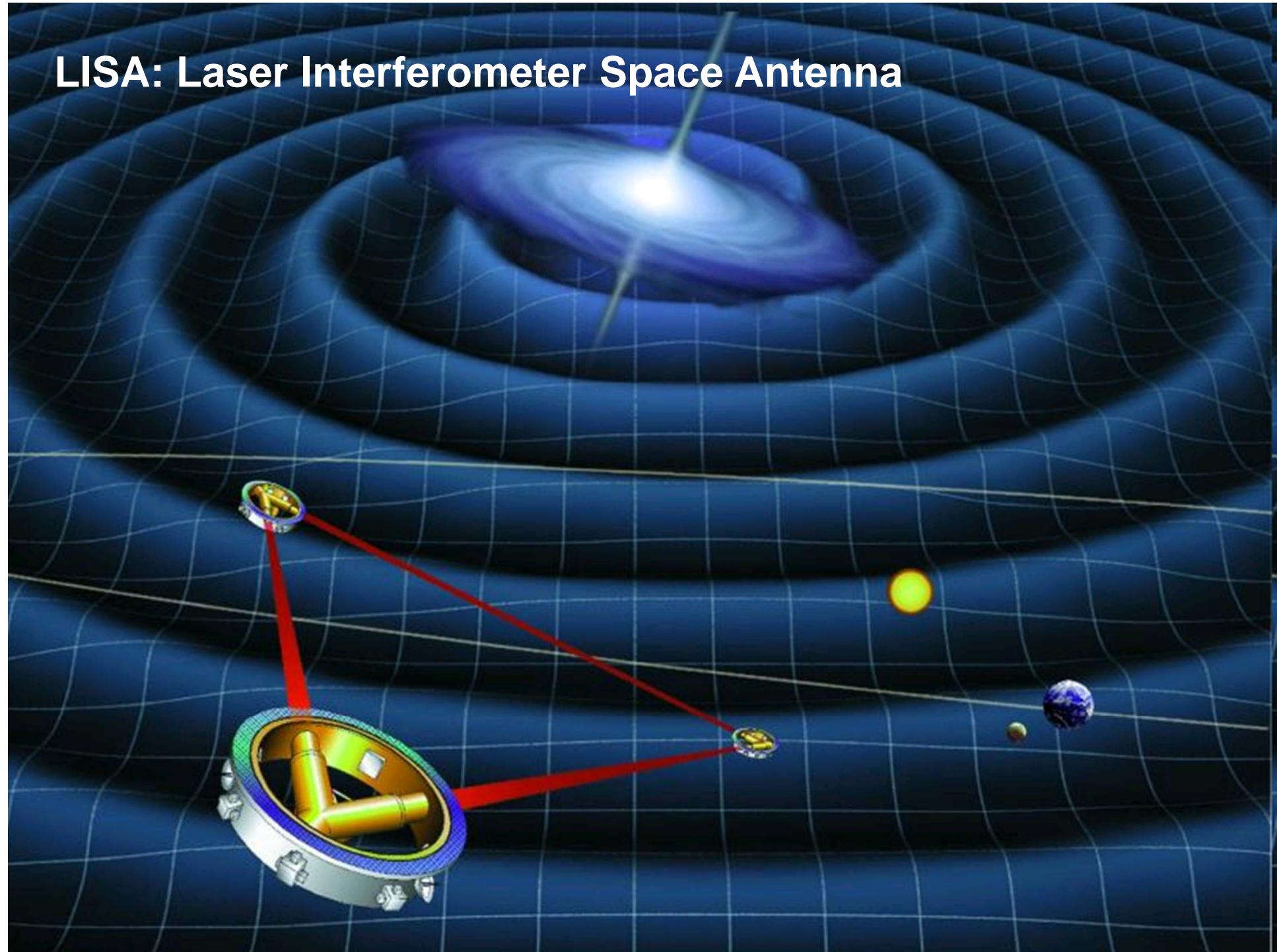


$$H_{\text{int}} \propto -\frac{\Phi_1 \Phi_2}{L_1 L_2} M_{12}(z)$$

M_{12} : mutual
inductance



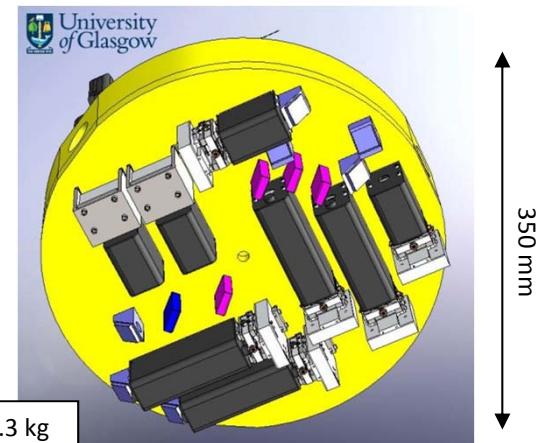
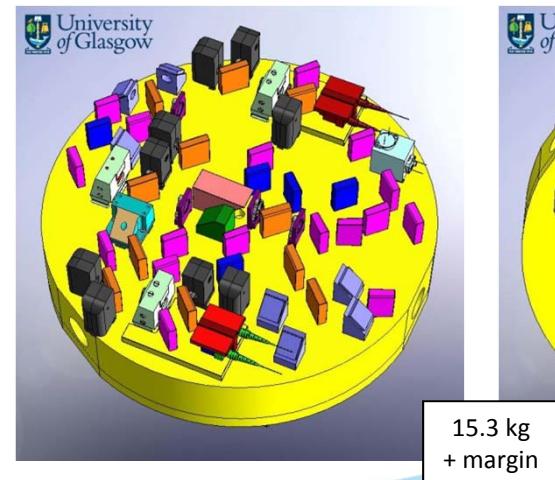
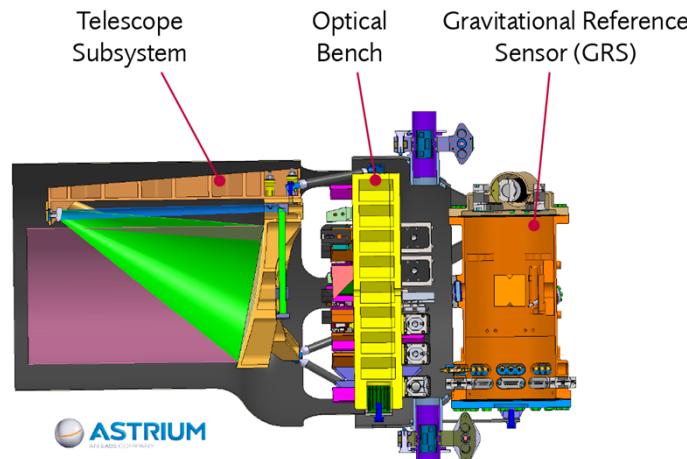
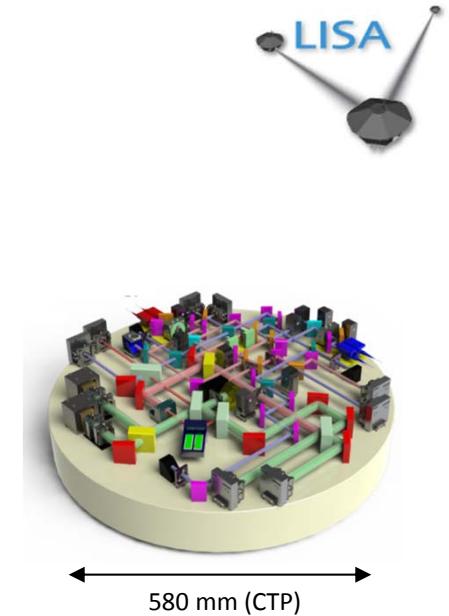
LISA: Laser Interferometer Space Antenna



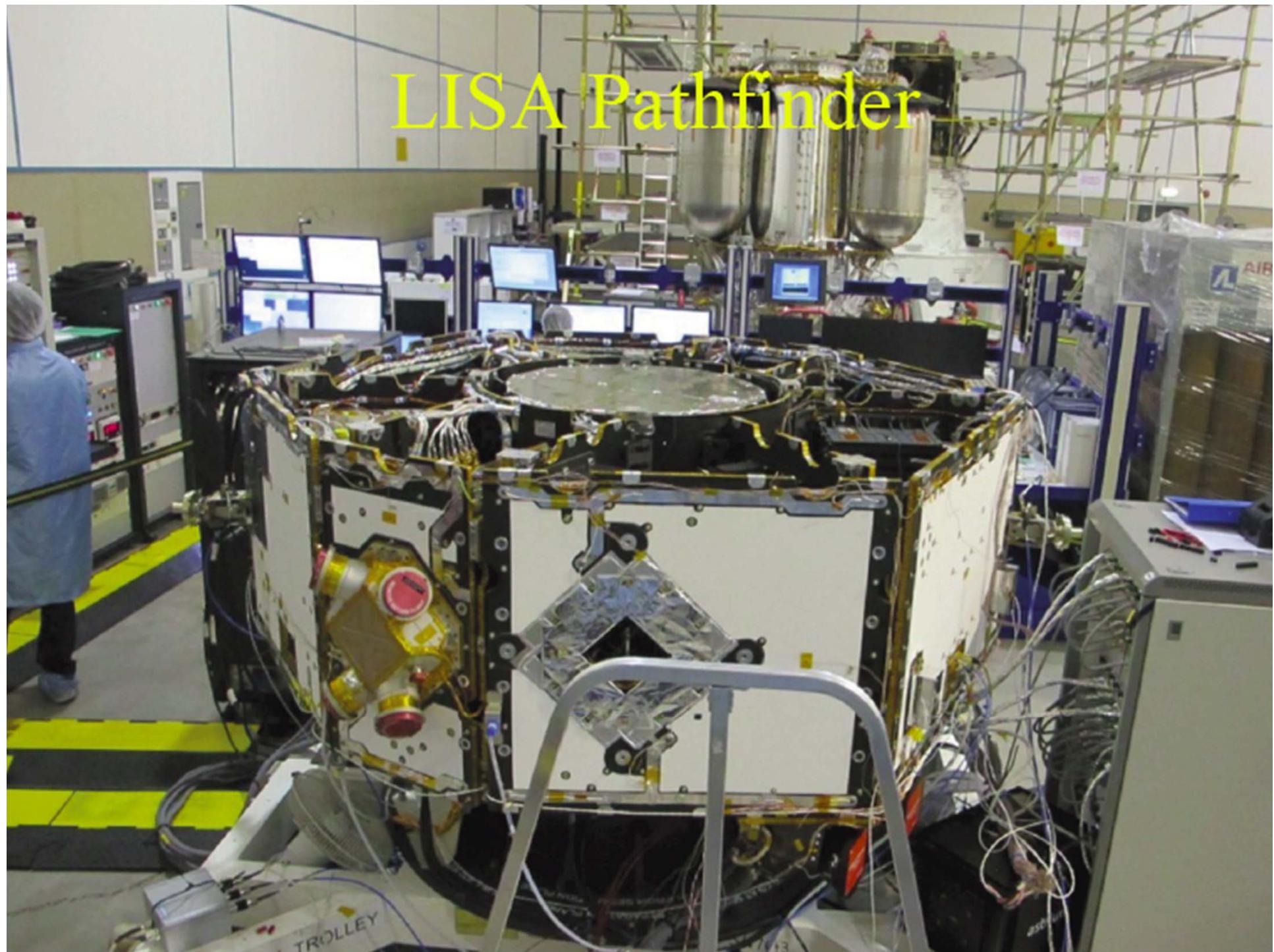
Payload Architecture

Optical Bench

- As in LMF, OB diameter drives payload and thus s/c height
 - Sizing coherent with reduced telescope dimensions is enabled by
 - Removal of PAAM, PAAM Metrology & Optical Truss
 - Double-sided OB**
 - Basic feasibility demonstrated by very detailed design, employing maximum heritage from LTP and LISA OB CTP



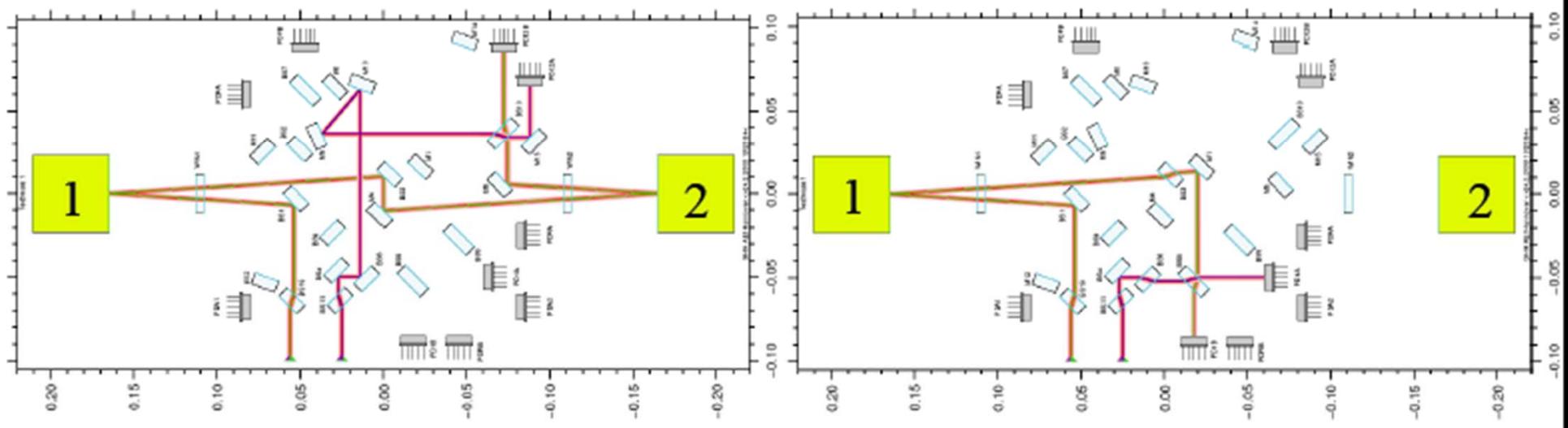
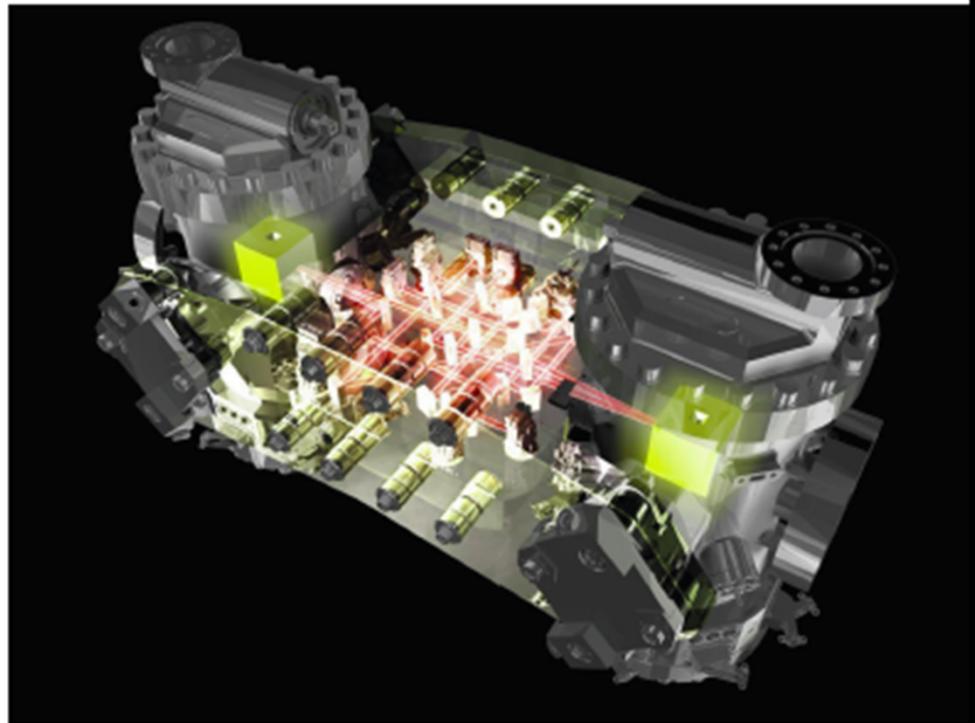
LISA Pathfinder





The LTP

- Two local interferometers on a high stability optical bench
- Two Au-PT test-masses enclosed in their GRS

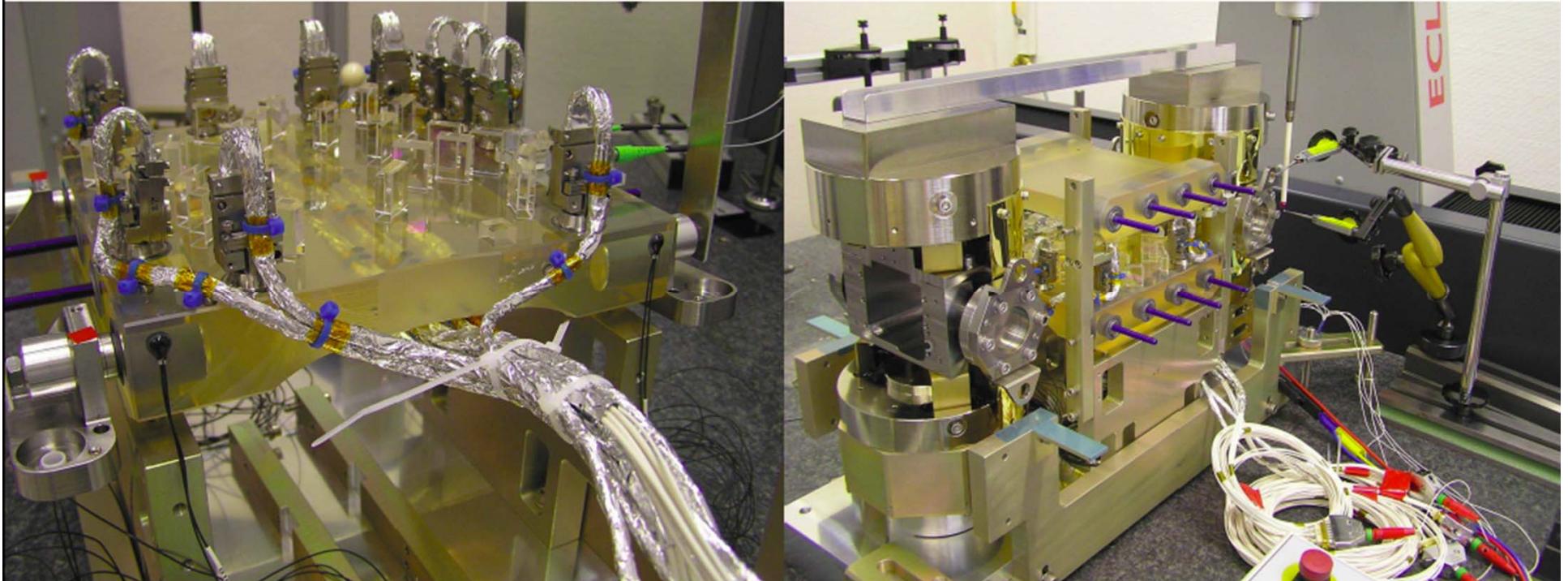


LTP flight configuration



The Optical Bench and Structure

- Thermo-optical qualification model of optical bench and structure
- Successfully tested end-to-end for optical performance (see F. Guzman talk)
- Strong candidate for flight

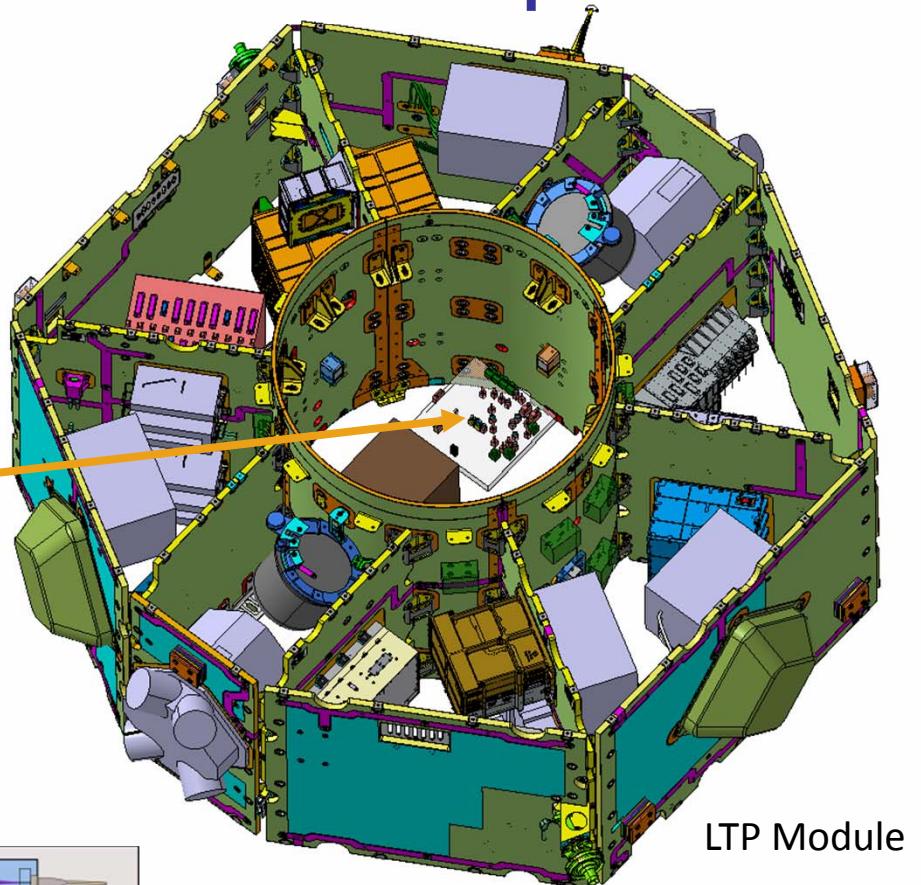
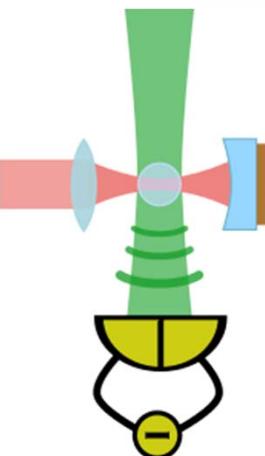
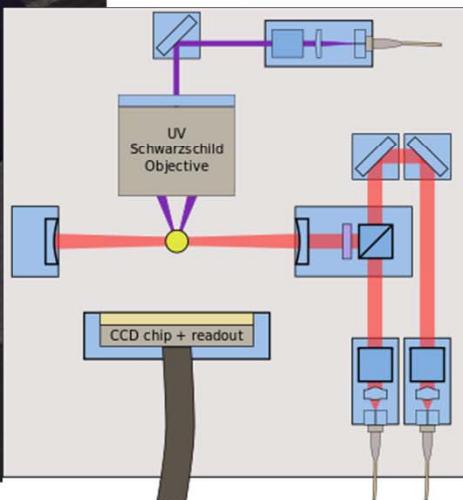
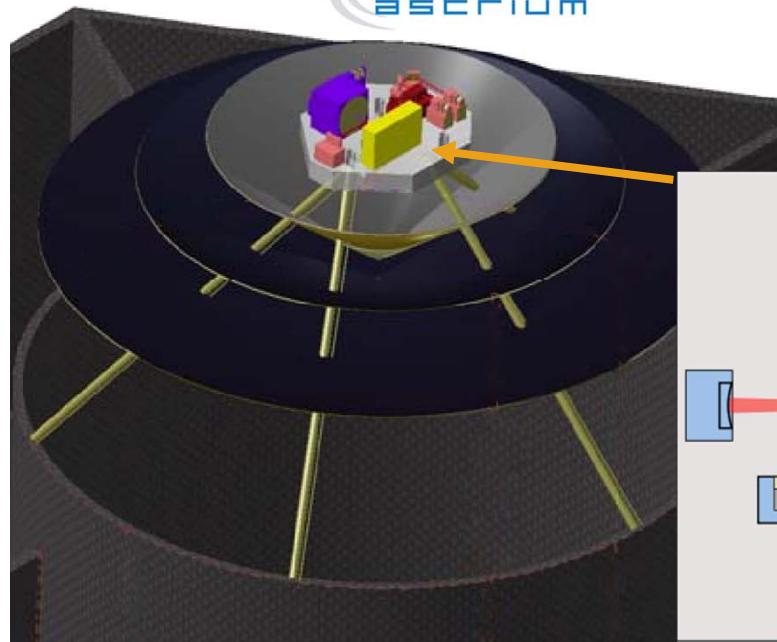


MAQRO: Macroscopic Quantum Resonators for Space

A possible space experiment under extreme conditions (vacuum, temperature):

$T_{env} \sim 10\text{ K}$, background pressure $\ll 10^{-15}\text{ mbar}$,
micro-gravity environment
→ Long fall times

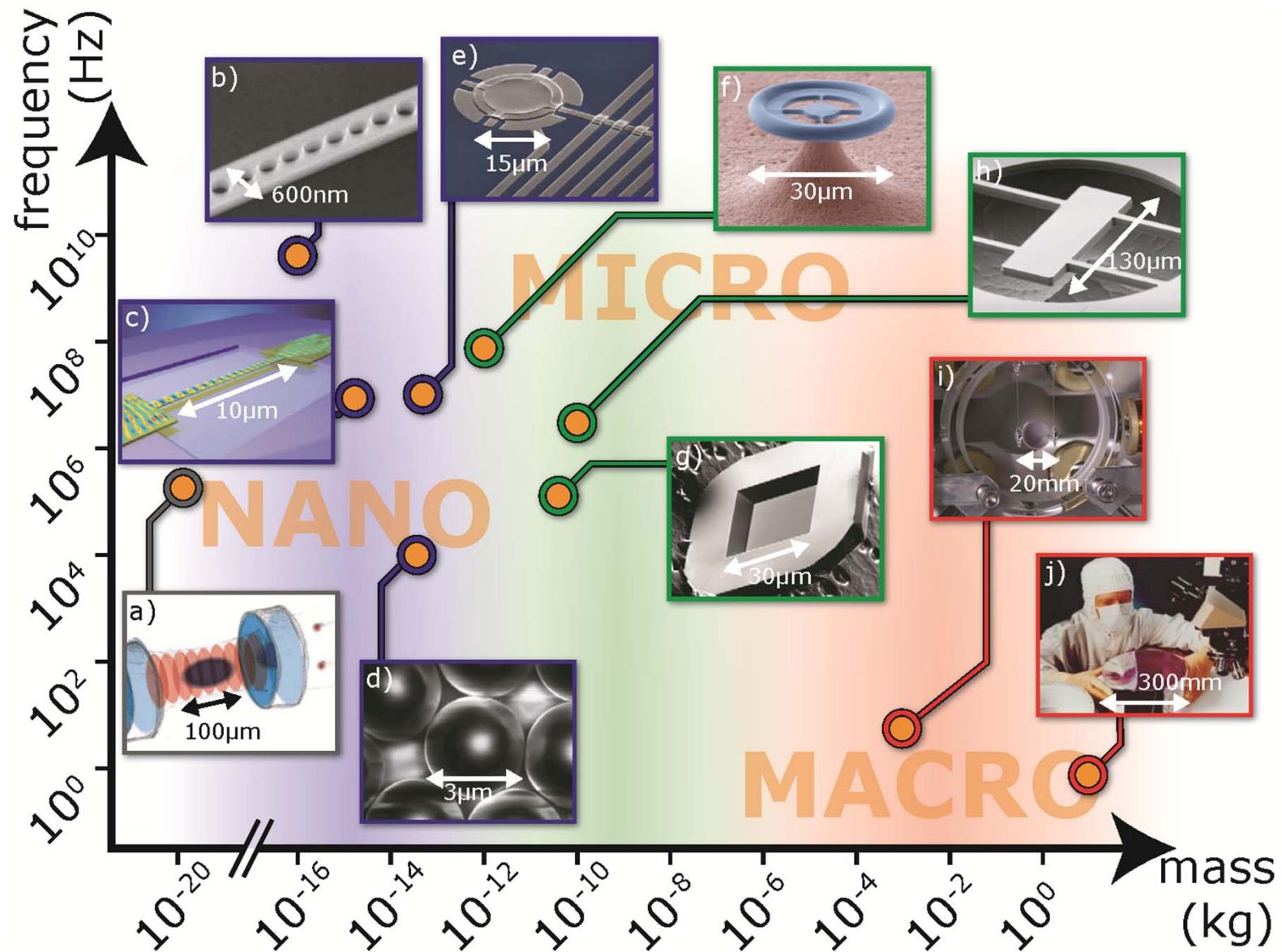
R. Kaltenbaek, Schwab, Aspelmeyer et al., arXiv:1201.4756
in collaboration with EADS ASTRIUM
Friedrichshafen



DECIDE

- macroscopic quantum states („Schrödinger Cat“)
- test quantum theory against macrorealistic models

Opto-mechanical devices (a few examples)



The role of gravity II:

„It seems clear to me that we're in trouble if we believe in quantum mechanics but don't quantize gravitational theory“

R. P. Feynman, 1957

Does gravity need to be quantized?

(Chapel Hill Conference)

NO → contradictions with the logical structure of quantum theory

→ **experimental consequences** (e.g. Bell-like theorems? Penrose?)

Classical gravity: localization of macro-objects

How to incorporate a Newtonian gravity field into quantum framework?

e.g. add **gravitational self-interaction** (Diosi, Penrose)

$$i\hbar\partial_t\Psi(t, \vec{x}) = \left(-\frac{\hbar^2}{2m}\Delta - Gm^2 \int \frac{|\Psi(t, \vec{y})|^2}{\|\vec{x} - \vec{y}\|} d^3y \right) \Psi(t, \vec{x})$$

Schrödinger-Newton equation (Diosi 1984)

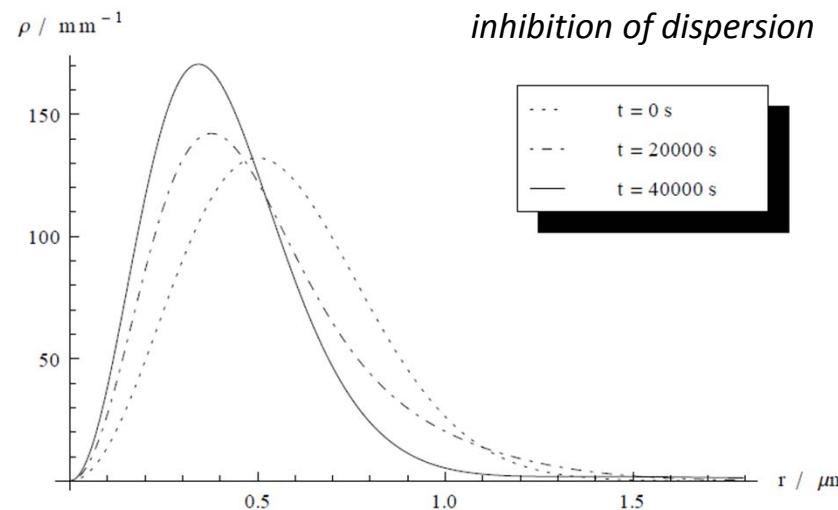


Figure 4: Collapsing wave packet for $m = 7 \times 10^9 \text{ u}$. Plotted is the radial probability density $\rho = 4\pi r^2 |\psi|^2$ against r at three different times.

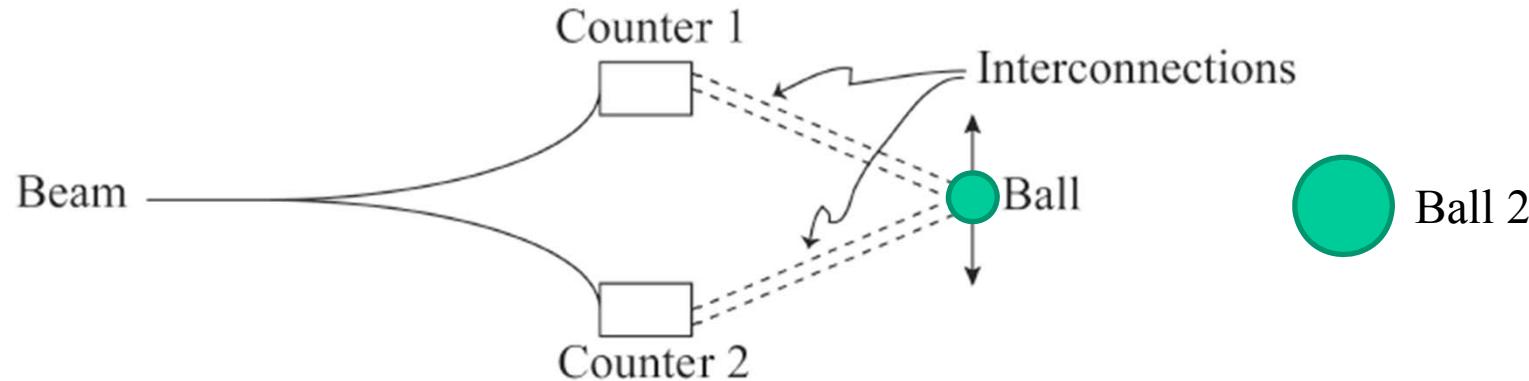
- gravitational inhibition of dispersion
- gravitationally bound states
- modified ground state (Gross-Pitaevskii)

$m = 10^{10} \text{ amu}$, $\sigma(0) = 500 \text{ nm}$
→ collapse time $t \sim 30,000 \text{ sec}$

$m = 10^{12} \text{ amu}$, $\sigma(0) = 500 \text{ fm}$
→ collapse time $t \sim 3 \times 10^{-6} \text{ sec}$

$\rightarrow R \sim 400 \mu\text{m}$, $\omega_m \sim 10^6 \text{ Hz}$!

An ultimate experiment? Entanglement by gravity...

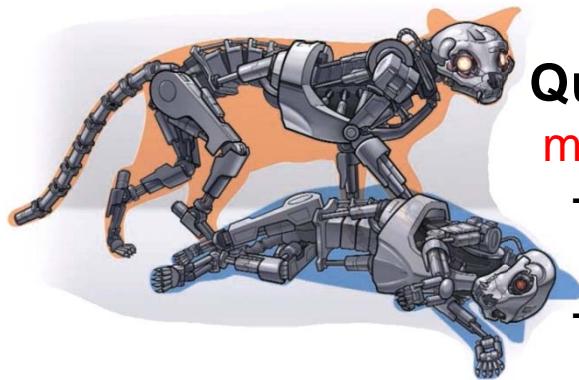


$$|\text{Ball1_u}\rangle + |\text{Ball1_d}\rangle \rightarrow |\text{Ball1_u}\rangle|\text{Ball2_u}\rangle + |\text{Ball1_d}\rangle|\text{Ball2_d}\rangle$$

FEYNMAN: "Therefore, there must be an amplitude for the gravitational field, *provided* that the amplification necessary to reach a mass which can produce a gravitational field big enough to serve as a link in the chain does not destroy the possibility of keeping quantum mechanics all the way. There is a *bare* possibility (which I shouldn't mention!) that quantum mechanics fails and becomes classical again when the amplification gets far enough, because of some minimum amplification which you can get across such a chain. But aside from that possibility, if you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment."

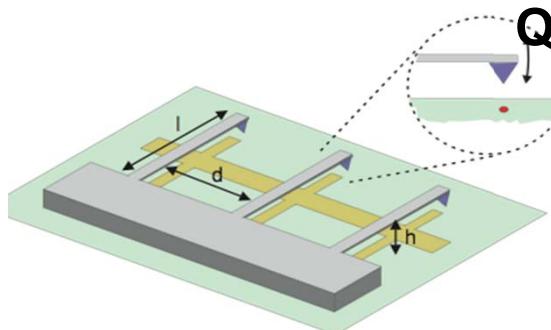
(Chapel Hill Conference 1957)

A new playground: adding „quantum“ to mechanics...



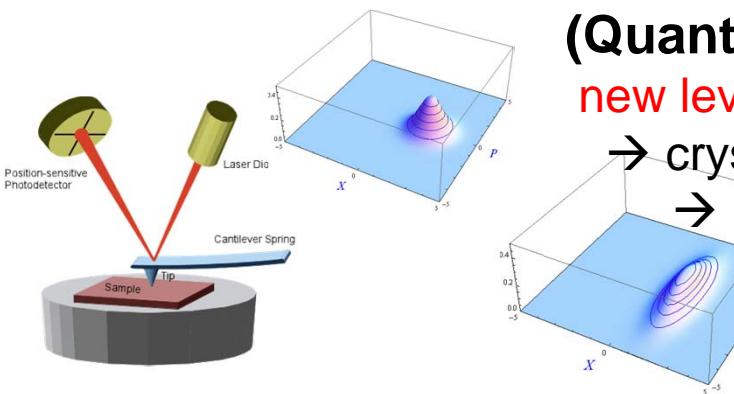
Quantum Foundations

macroscopic quantum physics
→ decoherence and the quantum measurement problem
→ quantum physics and gravity



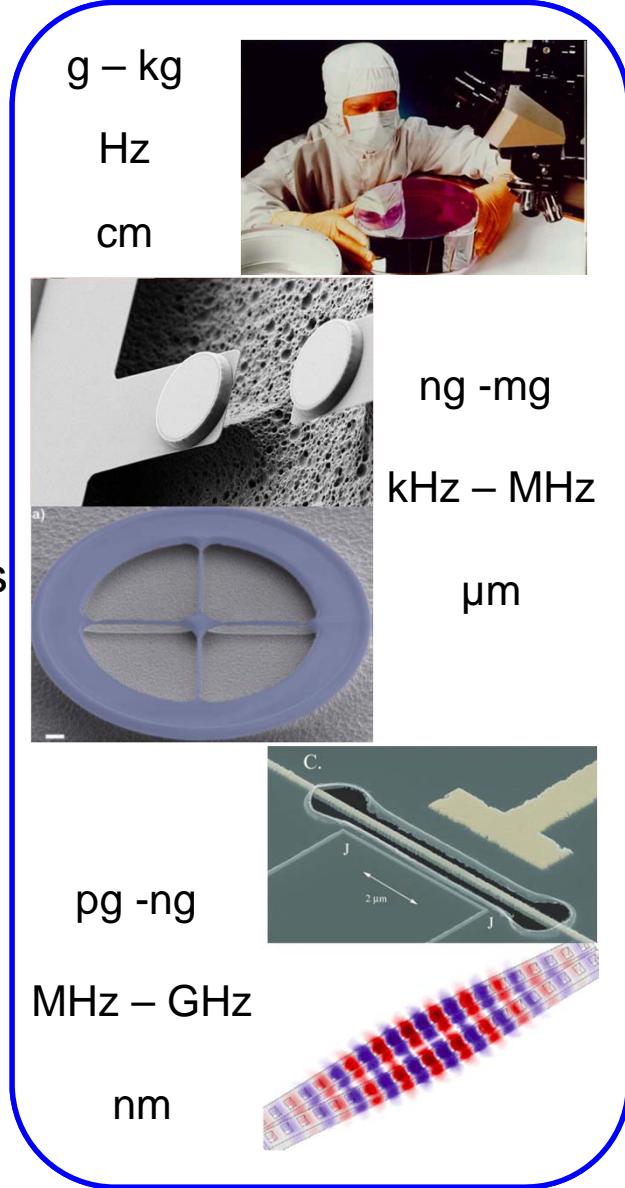
Quantum Information

novel on-chip architectures
→ coherent light-matter interfaces (transducers, memories)
→ strong photon-phonon nonlinearities



(Quantum) Measurement

new levels of accuracy
→ crystalline mirrors
→ measurements of G?



Our collaborators and discussion partners include...

Foundations of quantum physics:

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Raymond Chiao (UC Merced, USA)
Anthony J. Leggett (UIUC, USA)
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Quantum-“Mechanics” in Vienna: The Mirror Team 2012

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Quantum information interfaces (with K. Hammerer, P. Rabl, J. Eisert, O. Painter)

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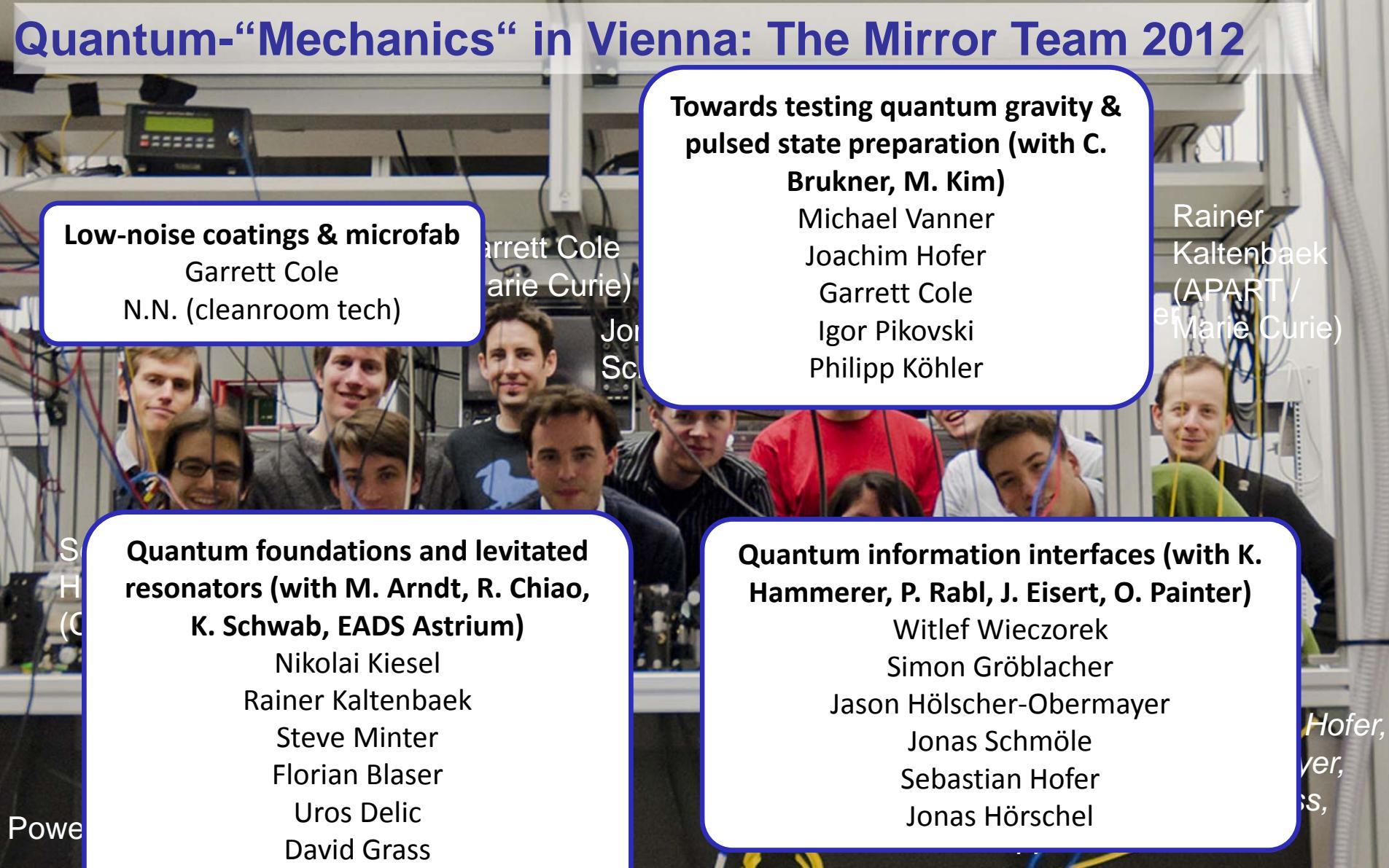
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Quantum-“Mechanics” in Vienna: The Mirror Team 2012



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